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Tests of Structure Functions using Leptons at CDF: W Asymmetry and Drell-Yan Production

The CDF Collaboration

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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Tests of Structure Functions Using Leptons at CDF: W Asymmetry and Drell-Yan Production

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Abstract

The charge asymmetry as a function of lepton rapidity, $A(y_l)$, has been measured at $\sqrt{s} = 1.8$ TeV for $|y_l| < 1.8$, using the W decays to electrons and muons recorded by CDF during the 1992-93 run of the Tevatron Collider. The luminosity used, approximately 20 pb^{-1}, and detector improvements resulted in a seven fold increase in statistics relative to the 1988-89 data. The increased statistics in the 1992-93 data allow for discrimination between sets of modern parton distribution functions. The results of this analysis demonstrate the value of collider data in the measurement of the proton's structure.

In addition, the Drell-Yan cross section has been measured using ≈ 4 pb^{-1} of dielectron and ≈ 2.5 pb^{-1} of dimuon data taken during the 1988-89 run. These measurements probe the quark distributions to $x < 0.01$ at high Q^2 where nonperturbative effects are minimal. Studies of Drell-Yan production in the ≈ 20 pb^{-1} data from the 1992-93 run are currently underway.

1 Introduction

The previous studies of W asymmetry [1] using the CDF [2] 1988-89 data indicated the potential of hadron collider detectors to contribute to understanding of parton structure functions. Figure 1 shows the lepton asymmetry in $W \to l\nu$ events, using the limited CDF 1988-89 data. The asymmetries were consistent with predictions of many of the available parton distributions sets. However, the low statistics of these data set did not allow for discrimination between various sets of parton distribution functions.

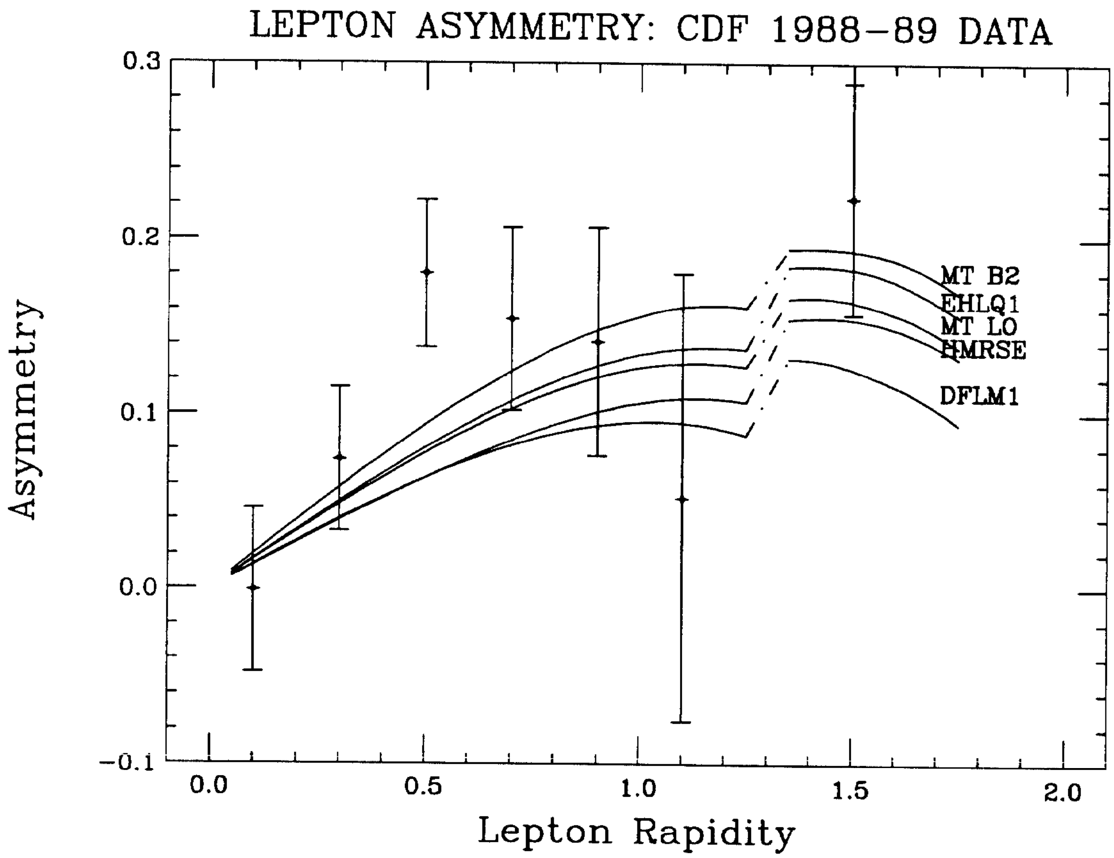


Figure 1: Lepton asymmetry in $W \rightarrow l\nu$ events, using the CDF 1988-89 data. The curves shown, which are predictions of representative parton distributions coupled to a leading-order calculation, are discontinuous because of the use of different transverse mass cuts in the central and plug regions (50 and 60 GeV/c^2), respectively [1]. These data have been superseded by more precise data shown in Fig. 4.

After the 1988-89 Collider run, the Plug EM calorimeter (PEM) has undergone significant repairs and improvements. New readout electronics and HV feedback systems were installed, resulting in significant noise reduction and better calibration of the detector. These improvements allowed CDF to lower the trigger thresholds in the PEM, and increase the rapidity coverage.

The asymmetry data is sensitive to the ratio of the d/u quark momentum distributions in the proton. The new precise 1992-93 data shown in Fig. 4 favor the most recent parton distributions and demonstrate the value of collider data in the measurement of the proton's structure. In particular it is found that of the two most current sets, those of Martin, Roberts and Stirling (MRS) [3] are favored over the sets produced by the CTEQ collaboration [4]. This difference is seen even though both sets are found to agree, at the level of the nuclear shadowing corrections, with the recent measurements of $F_2^{\mu n}/F_2^{\mu p}$ performed by NMC [5]. In this communication we present details of the final W asymmetry analysis from the 1992-93 data and results of the analysis of Drell-Yan production from earlier 1988-89 data.. This measurement probes the quark distributions to $x < 0.01$ at $Q^2 = M_W^2$, where nonperturbative effects are minimal.

2 Lepton asymmetry in W Boson Decays

W^+ (W^-) bosons are produced in $p\overline{p}$ collisions primarily by the annihilation of u (d) quarks from the proton and $\overline{d}$ ($\overline{u}$) quarks from the antiproton. Because the u quark tends to carry a larger fraction of the proton's momentum than the d quark the W^+ (W^-) tends to be boosted in the proton (antiproton) direction. The charge asymmetry in the production of W's, as a function of rapidity, is therefore related to the difference in the quark distributions at very high Q^2 ($\approx M_W^2$) and low x ($0.007 < x < 0.24$).

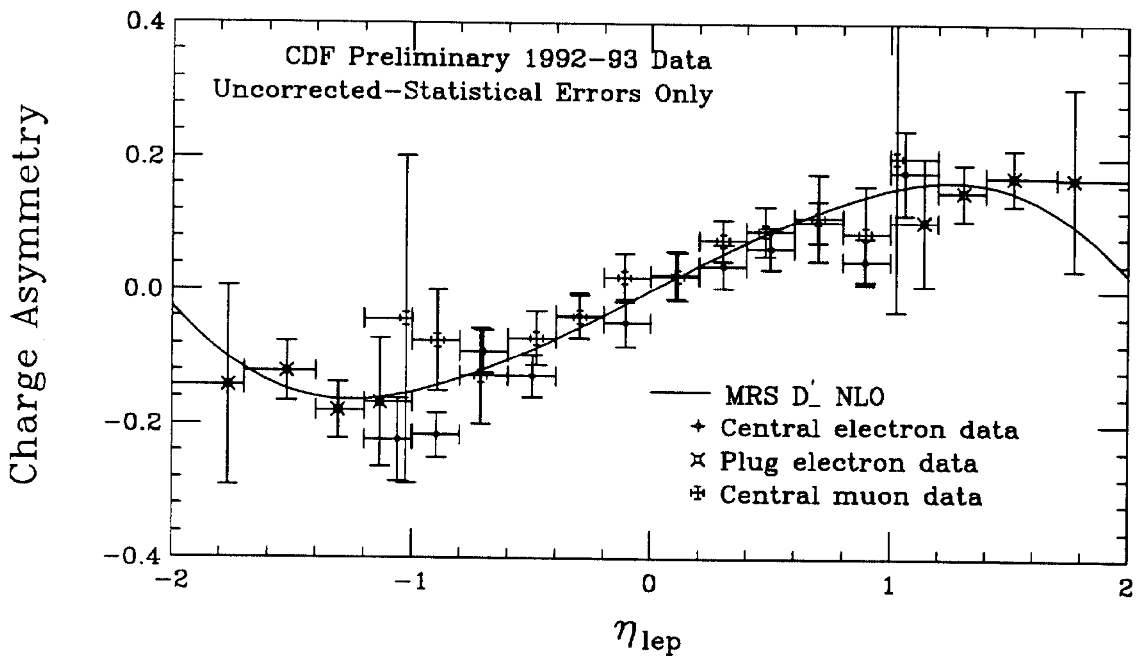
The W decay involves a neutrino, whose longitudinal momentum is undetermined. Therefore the quantity measured is the charge asymmetry of the decay leptons, which has an added contribution due to the V-A decay of the W. This portion of the asymmetry has been well measured by muon decay experiments; thus in comparisons to theory, one can attribute any deviations between prediction and measurement to the parton distributions used in the calculations. The asymmetry is defined as:

$$A(y_l) = \frac{d\sigma^+/dy_l - d\sigma^-/dy_l}{d\sigma^+/dy_l + d\sigma^-/dy_l} \tag{1}$$

where $d\sigma^+$ ($d\sigma^-$) is the cross section for W^+ (W^-) decay leptons as a function of lepton rapidity (positive rapidity is defined in the proton beam direction). As long as the acceptance and efficiencies for detecting l^+ and l^- are equal, this ratio of cross sections becomes simply the difference in the number of l^+ and l^- over the sum. Further, by CP invariance, the asymmetry at positive η is equal in magnitude and opposite in sign to that at negative η. Therefore, the value at positive η is combined with that at negative η reducing the effect of any possible differences in the efficiencies for l^+ and l^-.

W candidate events were required to have lepton transverse energy $E_T > 25\ GeV$ and missing transverse energy in the calorimeter $\not{E}_T > 25\ GeV$. In the case of muons, the $\not{E}_T$ is corrected for the muon's momentum. To further reduce QCD background, events with a jet whose E_T exceeded 20 GeV were rejected. Studies of the backgrounds and trigger acceptances [6] indicate that systematic errors do not impact the measurement.

Figure 2 shows the asymmetry before the values at positive η are combined with the opposite asymmetry at negative η. The level of agreement between the various detector types supports the results of the studies indicating that systematic effects are indeed small [6].



W^+ $\sim x_d$	0.15	0.08	0.03	0.01	0.007
$W^+\langle y\rangle$	−1.2	−0.6	.32	1.2	1.8
W^+ $\sim x_u$	0.01	0.02	0.06	0.15	0.27
W^- $\sim x_d$	0.007	0.01	0.03	0.08	0.15
$W^-\langle y\rangle$	−1.8	−1.2	−.32	0.6	1.2
W^- $\sim x_u$	0.27	0.15	0.06	0.02	0.01

Figure 2: The charge asymmetry, as a function of lepton η found in each of the detector types (Central EM, Plug EM and Central Muon). Also shown the average W^+ and W^- rapidity and the corresponding x values of the u and d quarks, are shown under the lepton η bin to which they contribute.

3 Comparisons with Predictions

Parton distributions [3, 4] are determined by fitting all the existing data which contain information on the quark and gluon momentum distributions. These data primarily originate from deep inelastic (DIS) electron, muon or neutrino scattering experiments on nucleons. This obviously makes it difficult to perform further checks of the validity of the assumptions which go into the fits, as by construction, the extracted PDF's agree with all the data. This is where the charge asymmetry is in a unique position: the asymmetry data was not used in any of the fits, and therefore provide an independent check.

Figures 3 and 4 show the large range of charge asymmetries predicted by the available PDF's. The most recent global analyses are those by Martin, Roberts and Stirling (MRS D'_-, MRS D'_0 and the preliminary MRS H) [3] and the CTEQ [4]

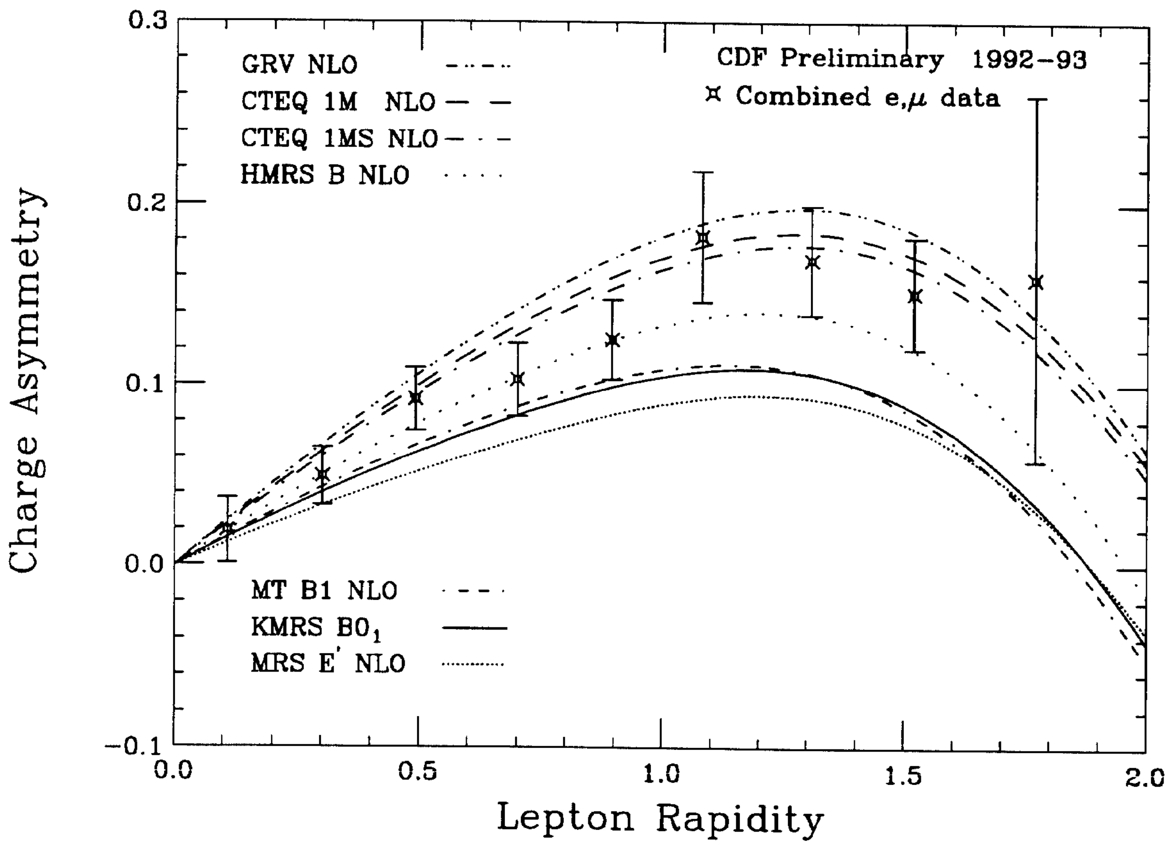


Figure 3: The older PDF's tend to predict lower asymmetries than do those which were fit using the recent NMC and CCFR data.

collaboration. The theoretical predictions for the W asymmetry were done in next to leading order (NLO) in QCD [10] using NLO parton distributions as input, and including all experimental cuts and detector effects [6]. The earlier sets such as HMRS B, MRS E′, KMRS B_0 and MT B1 tend to predict lower asymmetries, and most can be ruled out by this measurement. However, the earlier global fits did not have access to the recent DIS results from the CCFR [7] neutrino experiment and NMC [5] muon experiment, or the very recent *ep* collider data * from Hera [8, 9]. As a result, most of these PDF sets have been declared obsolete and retracted by their authors.

The GRV NLO parton distributions do not come from the data directly, "valence-like" distributions at very low Q^2 ($Q_0^2 = 0.3$ GeV^2) are evolved and then fitted to MRS distributions at a higher Q^2. The x and Q^2 dependencies are then determined by the renormalization group equations. This set of parton distributions has become of particular interest because they "predicted" the rise in the F_2^{ep} structure function

*This data is at a very low $x \sim 10^{-4}$, so it only indirectly impacts the W charge asymmetry.

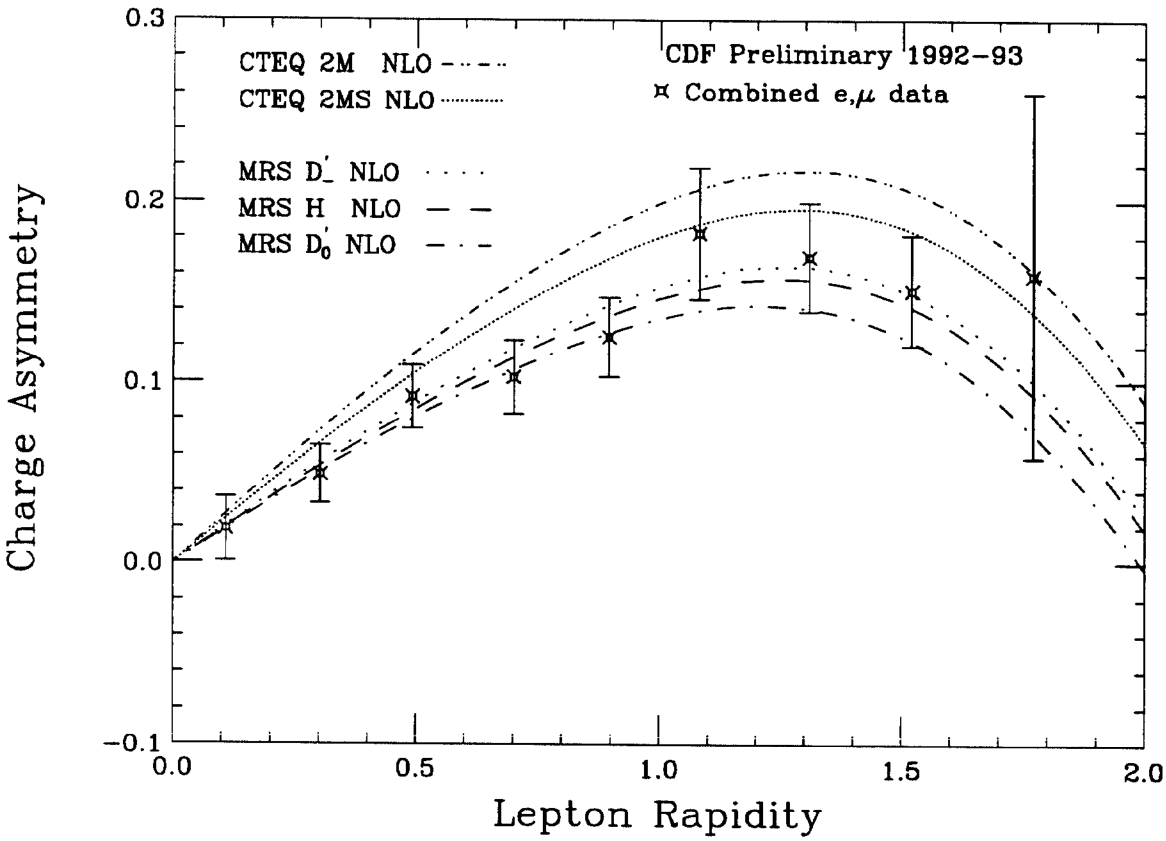


Figure 4: The charge asymmetry measured by CDF, compared to predictions of the latest PDF's. The data are fully corrected for trigger and backgrounds and the systematic errors are included.

at $x \sim 10^{-4}$, and they fit the Hera data quite well. However, as can be seen from Fig. 3 the GRV PDF's do not reproduce the observed W charge asymmetry very well.

Therefore it is of most interest to concentrate on the recent MRS and CTEQ fits. Both groups have had access to the same DIS data, but as Figure 4 shows, they differ considerably in their charge asymmetry predictions. To quantify the degree to which the various PDF's reproduce the data, Table 1 lists the results of χ^2 tests of the goodness of fit. Because there is no differentiating power in the first and last η bins, the χ^2 is also calculated for the seven bins ($0.2 < |\eta| < 1.7$) as well as for the error weighted mean of the seven data points (the predicted asymmetries were calculated in the identical manner). The motivation for the last test is that the various predicted asymmetries tend to differ systematically from one another. All the modern PDF's predict essentially the same shape, just their overall magnitude differ.

As expected, almost all the older sets have poor χ^2's, though HMRS B is still marginally acceptable. However even the more recently updated CTEQ2 distribu-

PDF Set	$\|y\| < 2$ (9 dof) χ^2	Prob(χ^2)	$0.2 < \|y\| < 1.7$ (7 dof) χ^2	Prob(χ^2)	$\overline{A}(y)$ $0.2 < \|y\| < 1.7$ $\Delta\sigma$	Prob(σ^2)
CTEQ 2M	25.	<0.01	24.	< 0.01	4.6	< 0.01
CTEQ 2MS	11.	0.27	11.	0.15	2.9	< 0.01
CTEQ 1M	6.4	0.71	6.1	0.52	2.1	0.04
CTEQ 1MS	4.1	0.90	3.9	0.79	1.5	0.13
MT B1	19.	0.03	17.	0.02	-3.2	< 0.01
MRS H prelim.	2.2	0.99	1.7	0.97	-0.1	0.96
MRS D'_-	2.3	0.99	1.9	0.97	0.5	0.61
MRS D'_0	4.4	0.93	3.6	0.83	-0.9	0.35
HMRS B	5.1	0.83	4.2	0.75	-1.2	0.23
KMRS B_0	20.	0.02	19.	0.01	-3.6	< 0.01
MRS E'	32.	< 0.01	30.	< 0.01	-4.9	< 0.01
GRV NLO	12.	0.23	12.	0.12	3.0	< 0.01

Table 1: The results of χ^2 comparisons between the predicted asymmetries (calculated at NLO) for several NLO PDF's including the most recent MRS and CTEQ distributions. The comparison of the weighted means ($\overline{A}(y)$) is sensitive to systematic shifts, and indicates the MRS H distributions fit the asymmetry data best.

tions also fail to reproduce the observed charge asymmetry. The PDF set for which the CTEQ collaboration gets the lowest χ^2 when fitting the DIS data, CTEQ 2M, disagrees with the asymmetry data (weighted mean, $\overline{A}(y)$) at the 4 standard deviations level. In contrast, the MRS distributions fit remarkably well with the most recent MRS H reproducing the asymmetry data perfectly. These two distributions are the result of fitting to some of the same DIS data, including the Hera data, yet the asymmetry data favor the MRS distributions.

4 Measuring the Proton Structure

The rapidity of the W's which contribute to each of the lepton η bins was determined using Dyrad [10] W/Z NLO Monte Carlo. Of course this is also sensitive to the detector acceptances, which are not modelled perfectly. However, even the qualitative results are useful in the understanding of the relationship between the rapidity of the W and its decay lepton. Figure 2 shows the average rapidity of the W's which contribute to particular η_{lep} bin and the x values these rapidities correspond to. One sees that the lepton asymmetry carries much the same information as the W's.

The W charge asymmetry is particularly sensitive to the slope of the $d(x)/u(x)$ ratio [11] in the x range $0.007 - 0.27$ (see Figure 2), whereas the $F_2^{\mu n}/F_2^{\mu p}$ measure-

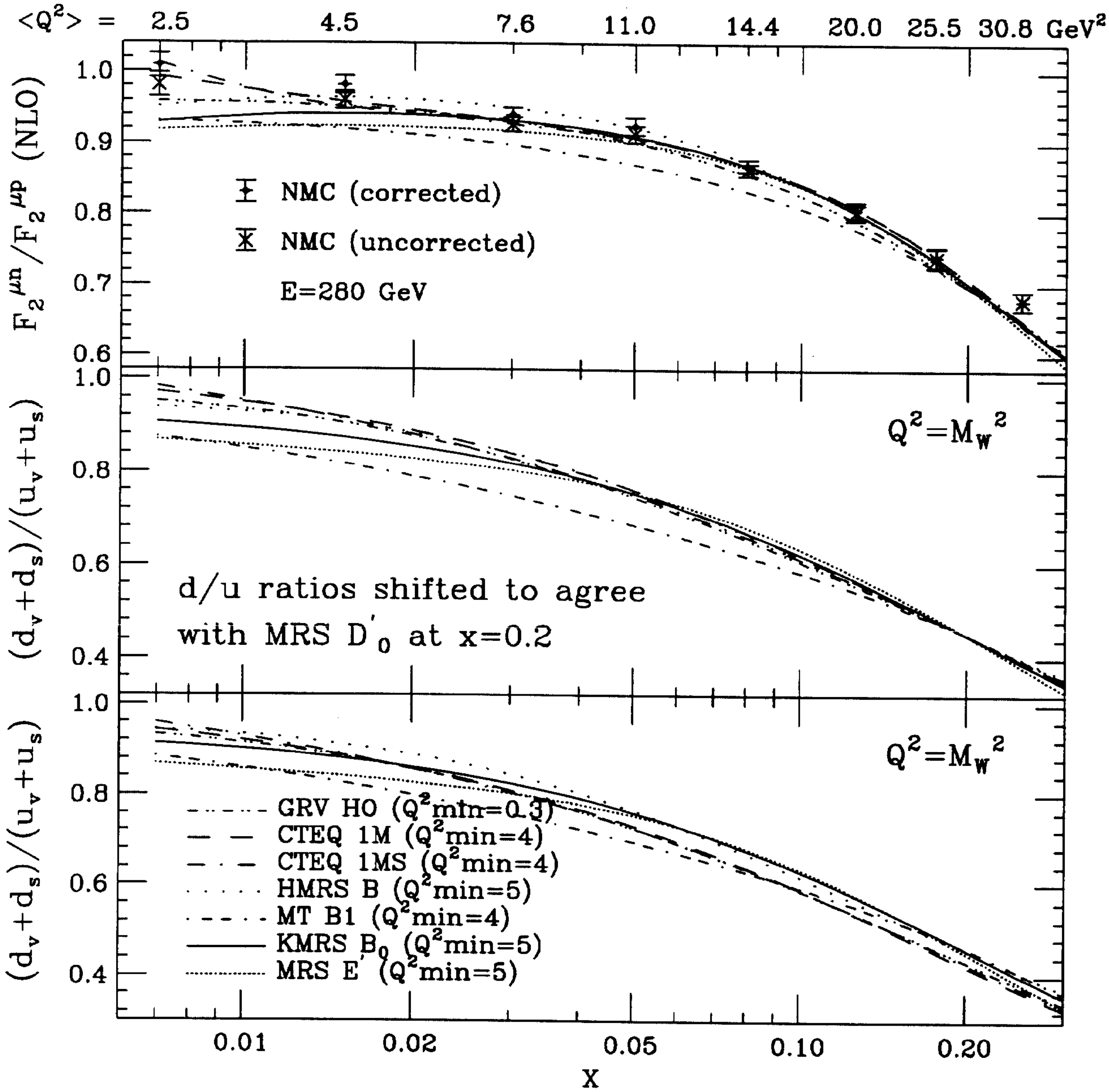


Figure 5: $F_2^{\mu n}/F_2^{\mu p}$ derived from the NMC [5] data, before and after correcting for shadowing in the deuteron [13] (top). The $F_2^{\mu n}/F_2^{\mu p}$ predictions were done at NLO and take the different Q^2's at each data point into account. The predicted charge asymmetries for these PDF's can be found in Figure 3. For Q^2 values below the minimum Q^2 stated at the bottom of the figure, the parton distributions were logarithmically extrapolated.

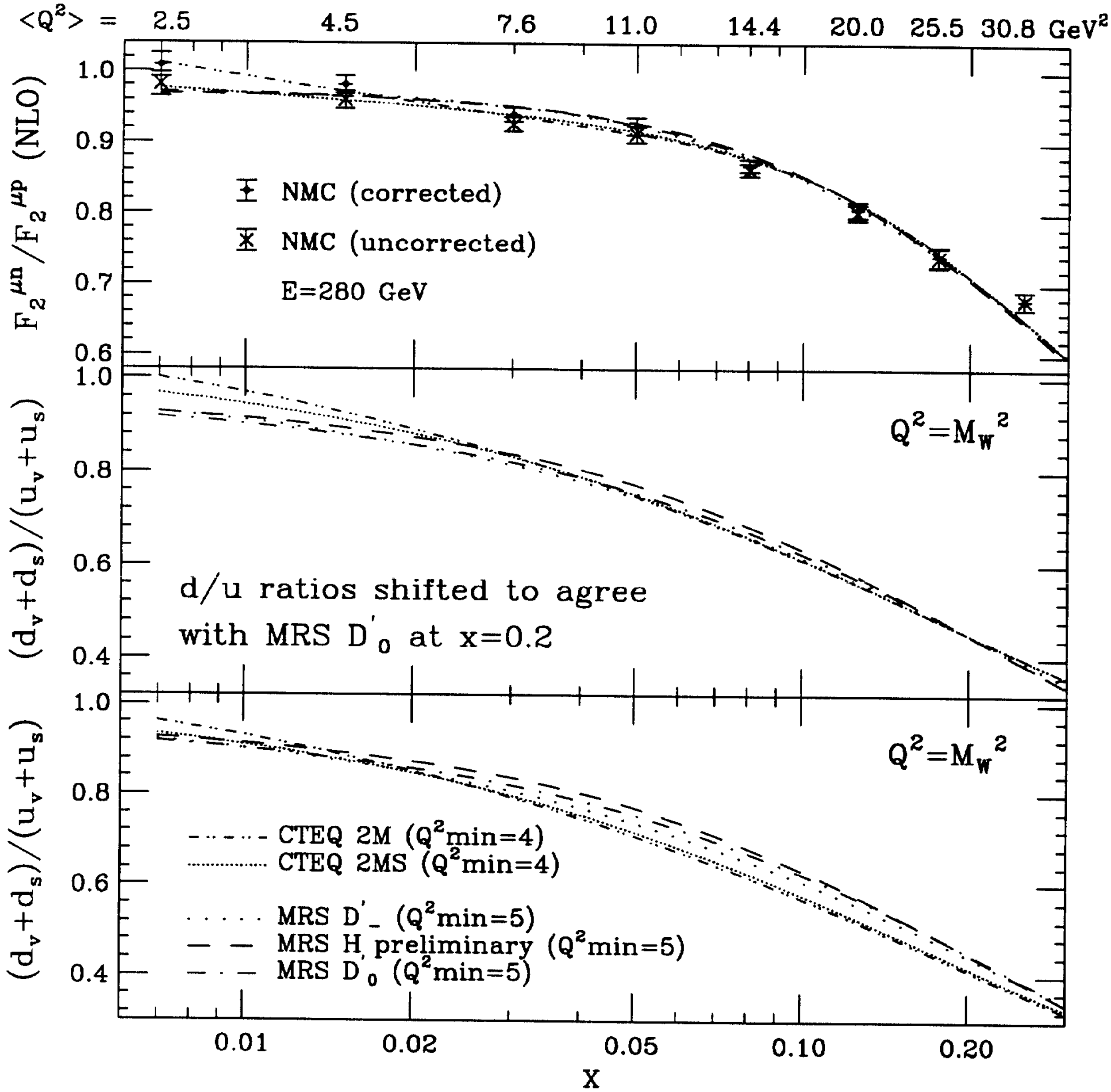


Figure 6: $F_2^{\mu n}/F_2^{\mu p}$ for some of the most recent PDF's compared to the NMC data (same as in Figure 5). The predicted charge asymmetries for these PDF's can be found in Figure 4. For Q^2 values below the minimum Q^2 stated at the bottom of the figure, the parton distributions were logarithmically extrapolated.

ments are sensitive to the magnitude of this ratio. Recently NMC has measured $F_2^{\mu n}/F_2^{\mu p}$ [5] over an x range comparable to that accessible at CDF (though at a very different Q^2). Their data, both before and after correcting for deuteron shadowing effects [12, 13], are plotted in Figures 5 and 6 along with several NLO predictions. Also shown are the d/u ratios after being shifted by a constant so they agree with MRS D_0' at $x = 0.2$. From the comparisons of the shifted ratios with the corresponding asymmetries we find that PDF's which predict the largest difference between the d/u ratio at small x relative to moderate x, also predict largest charge asymmetries.

Figure 6 compares only the latest fits performed by the MRS and CTEQ collaborations. One sees that even though the MRS and CTEQ fits have very different d/u distributions (and thus very different charge asymmetry predictions) the $F_2^{\mu n}/F_2^{\mu p}$ predictions agree at the level of the 100% uncertainty in the deuteron shadowing corrections. This is because the $F_2^{\mu n}/F_2^{\mu p}$ ratio is also sensitive to the differences in the $\overline{u}$ and $\overline{d}$ distributions, whereas the $A(y)$ asymmetry is not. For example, the CTEQ's parameterization of the $\overline{u}$ and $\overline{d}$ sea distributions compensates for their steep d/u ratio and leads to a prediction for $F_2^{\mu n}/F_2^{\mu p}$ which is consistent with the NMC data but is inconsistent with CDF $A(y)$ asymmetry measurement.

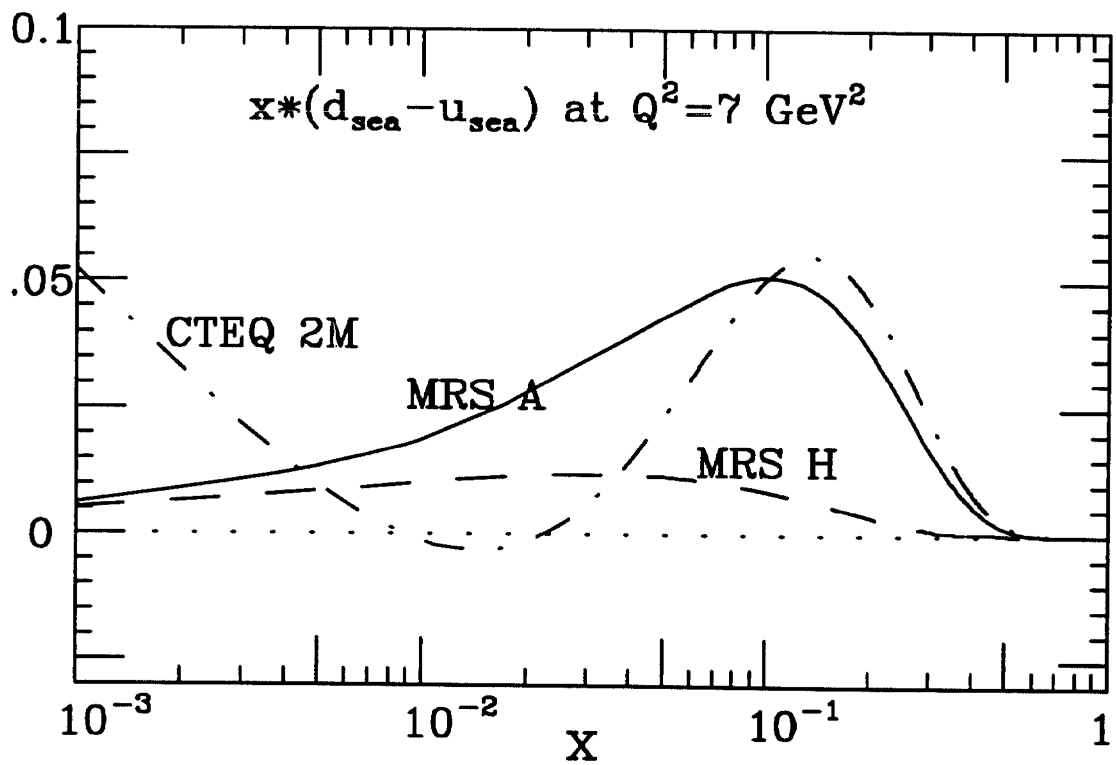


Figure 7: Quantity $\overline{d}-\overline{u}$ as a function of x for the MRS H (dashed line) and CTEQ 2M (dot-dashed line) fits evaluated at Q^2= 7 GeV^2. Solid line represents the MRS A parametrization, which includes both the W asymmetry data presented here, and the recent NA51 [16] Drell Yan results for $\overline{d}-\overline{u}$ at x=0.18.

The asymmetry data also provide an independent means by which we can test the series of assumptions about theory and experiment that goes into a particular set of global fits to the nucleon's structure. Specifically, the MRS H fit imposes a physically motivated constraint that $\bar{d} = \bar{u}$ as x approaches 0, and also requires the quantity $\bar{d} - \bar{u}$ to be positive definite in order to satisfy the violations of the Gottfried Sum Rule [14] observed in the integral of the NMC $F_2^{\mu p} - F_2^{\mu n}$ data. The CTEQ collaboration attempts to fit the NMC $F_2^{\mu n}$ and $F_2^{\mu p}$ data in much more detail with more free parameters, and without the $\bar{d} = \bar{u}$ at $x = 0$ constraint. The resulting CTEQ 2M parametrization for $\bar{d} - \bar{u}$ is large when extrapolated to very small x, and oscillates around 0 for larger values of x. Figure 7 (from Ref [15]) shows the quantity $\bar{d} - \bar{u}$ as a function of x for both the MRS H and CTEQ 2M fits evaluated at $Q^2 = 7$ GeV^2. The very different $\bar{d} - \bar{u}$ parametrization of MRS H and CTEQ 2M also leada to correspondingly different d/u parametrizations when fitting to the same $F_2^{\mu n}$ and $F_2^{\mu p}$ data †.

5 W Asymmetry Conclusions

The prior measurement of the charge asymmetry in W decays was severly hampered by statistics as well as detector problems, but even so the measurement hinted that the predicted asymmetries were too low, thus implying that the d/u ratio was steeper than most parton distributions predicted. With the advent of recent high statistics, precision deep inelastic electron, muon and neutrino scattering experiments, the global fits to the proton structure all predict steeper d/u quark distributions. But as the x range probed in these experiments has decreased and the statistics increased, as in the muon experiments on hydrogen and deuterium, the theoretical uncertainties in the extraction of the quark distributions due to higher twist effects at low Q^2 [17], and the additional uncertainty from shadowing corrections in the deuteron, have become very important. The fact that the charge asymmetry is able to distinguish between parton distributions which fit the NMC $F_2^{\mu n}/F_2^{\mu p}$ measurements, demonstrates that already its sensitivity to the d/u ratio at very low x is better than that of the muon scattering experiments. In addition to having very low systematics, the asymmetry data does not have the deuteron shadowing uncertainties, nor is it sensitive to any low Q^2 higher twist corrections.

The systematic errors of CDF W charge asymmetry measurement will remain negligible through the current run of the Tevatron and into the next. Even with four times the data (100 pb^{-1} of integrated luminosity) the W charge asymmetry's error will be dominated by the statistics available. In the future it is clear that the charge

†The curve for the most recent MRS A represents a parametrization [15], which includes both the W asymmetry data presented here, and the recent NA51 [16] Drell Yan results for $\bar{d} - \bar{u}$ at x=0.18. The weighted mean of W asymmetry, $\overline{A}(y)$ for MRS A parametrization is ≈ 0.9 standard deviations above the value measured by the CDF.

asymmetry will be able to play an even more significant role in the determination of the proton's structure.

6 Measurement of Drell-Yan Dilepton Pair Differential Cross-Section

The Drell-Yan events are easily reconstructed from the measured properties of the decay leptons. The CDF experiment has measured [18] the differential cross section $d^2\sigma/dMdy_{|y|<1}$, over the mass range $11 < M < 150\ GeV/c^2$ using dielectron and dimuon data from 1988-89 collider run ($\approx 4\ pb^{-1}$).

The differential Drell-Yan cross section provides information on the magnitude of the quark distributions in the x range 0.006-0.03 over a Q^2 range of 121-3600 GeV^2. The results show $1/M^3$ dependence as is expected from naive Drell-Yan model.

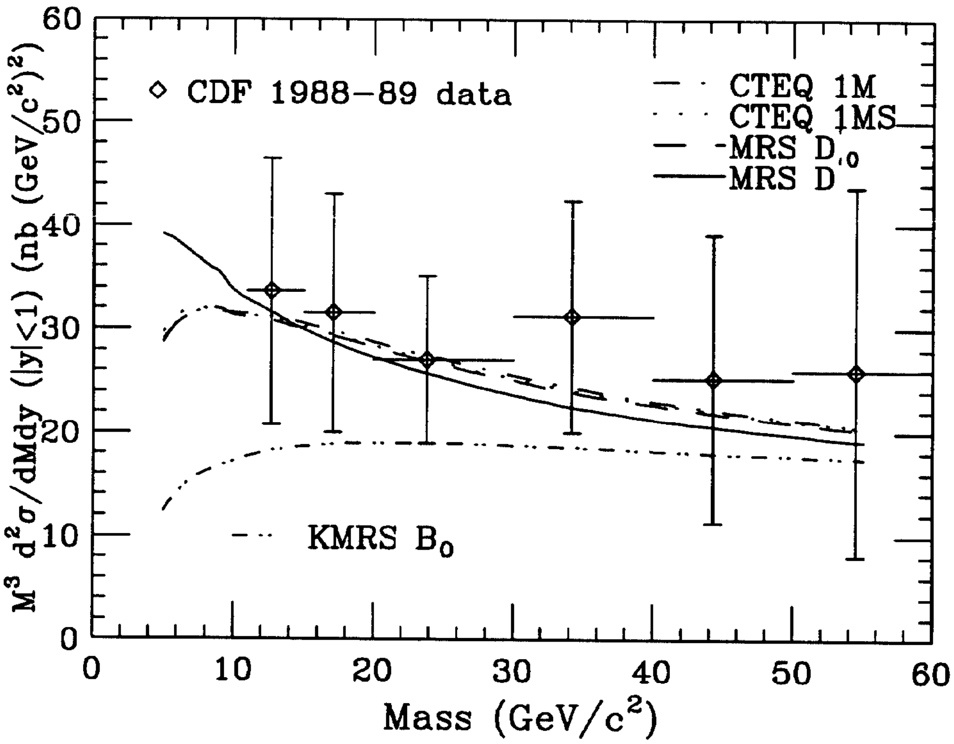


Figure 8: Drell-Yan electron and muon pair production compared to NLO predictions for the 1988-89 (4 pb^{-1}) data.

Figure 8 shows the differential Drell-Yan cross section as a function of dilepton invariant mass. The data is compared to NLO predictions. The measurement favors those distributions which have the largest quark contribution in the x interval 0.006 to 0.03, in particular the sets which used the most recent DIS data. However, as was the case for the 1988-89 W asymmetry data, the statistics were limited.

7 Outlook

Using the 1992-93 data ($\approx 20\ pb^{-1}$) we can look forward to a factor of six improvement in statistics for the Drell-Yan analysis. An additional factor of four is expected at the end of 1995 ($\approx 100\ pb^{-1}$).

One of the main sources of the background to the Drell-Yan signal are heavy quark decays. It consists of pairs, mostly $b\bar{b}$, for which both quarks decay semileptonically. The analysis of 1988-89 data exploited the fact that the background events tend to have non-isolated lepton candidates (since the leptons are typically surrounded by the other particles from jets), while leptons from Drell-Yan process are expected to be isolated. The installation of a silicon microstrip vertex detector (SVX) in 1992 will additionally allow us to discriminate against the heavy flavor background using the secondary vertex information to tag b's. Figure 9 shows the effective proper decay length, $c\tau_{eff}$ for a sample of unbiased jets that are found in events passing the 50 GeV jet trigger compared with the Monte Carlo simulation of b-quark and c-quark decays and 'fake' decays caused by mismeasured tracks. The rejection of backgrounds from two semileptonic decays of heavy flavors is especially important in the low mass region ($M_{ll} \approx 10$ GeV) where different parton distribution functions yield different cross sections.

In addition to extending the Drell-Yan analysis to lower values of dilepton mass, the higher statistics of run 1B will allow us to bin the data in both M_{ll} and in dilepton rapidity bins, thus yielding further discrimination between different parton distributions. It is clear that the Drell-Yan analysis could provide a strong constraints on the quark distributions, in addition to the powerful constraints from W asymmetry data.

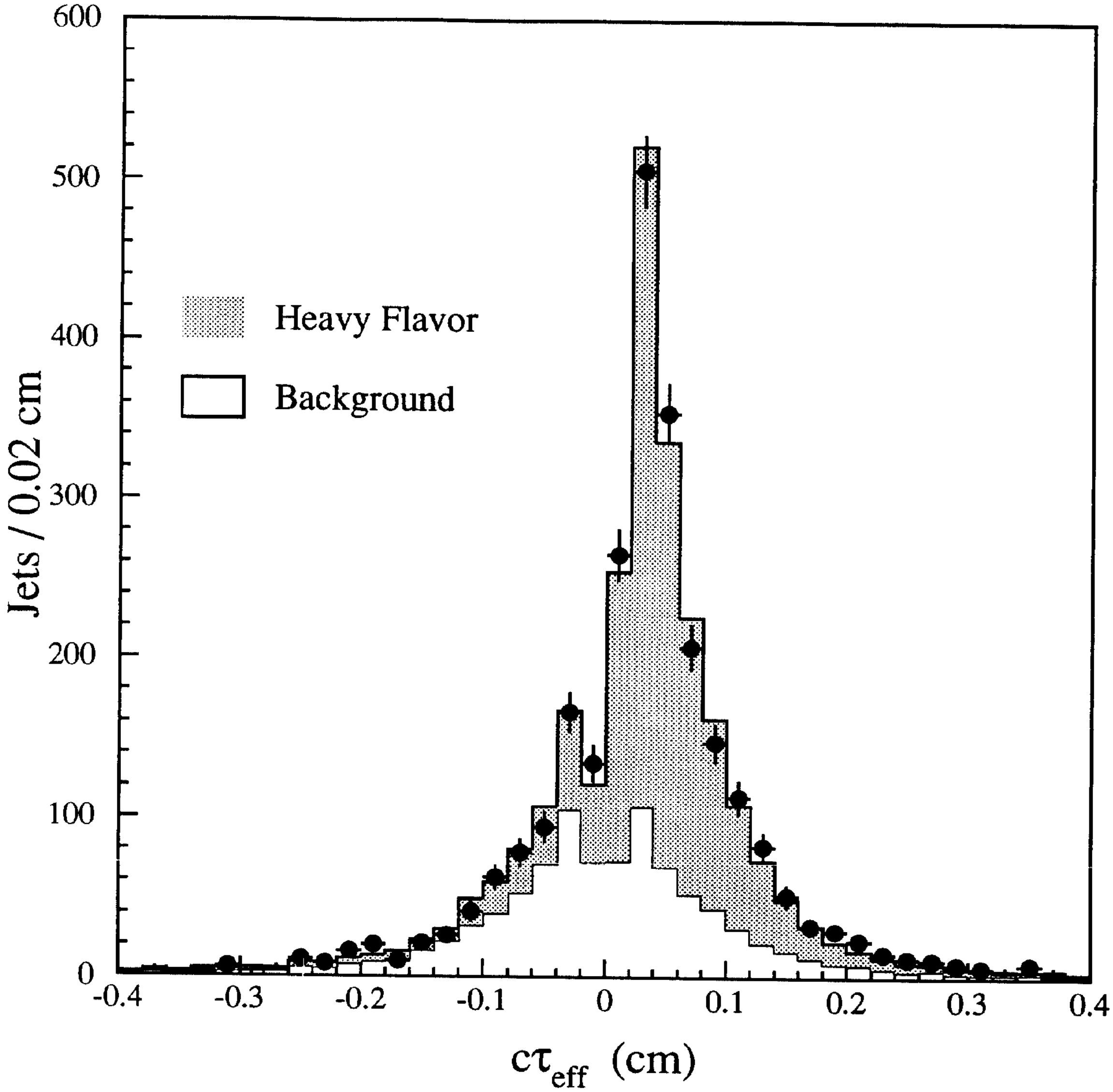


Figure 9: The effective proper decay length, $c\tau_{eff}$ for a sample of unbiased jets that are found in events passing the 50 GeV jet trigger compared with the Monte Carlo simulation of b-quark and c-quark decays and 'fake' decays caused by mismeasured tracks. The fit gives the relative fractions of positive $c\tau_{eff}$ tags from heavy flavor and background to be approximately 75% and 25% respectively.

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